Unsteady Hydrodynamics of the Maneuvering Submarine

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Abstract

The availability of fast parallel computers able to execute extremely large problems, together with the development of a fully unsteady Reynolds-averaged Navier-Stokes (UnRANS) code for turbulent flow, has for the first time permitted addressing the prediction of maneuvering submarine hydrodynamics without the use of extensive simplifying approximations. One such code, UNCLE, is being utilized and modified to compute the complex flowfield around rotating propulsors, around the hull and appendages, and finally around the complete vehicle, predicting the forces and the resulting trajectory. This project encompasses the prediction of unsteady, three-dimensional, turbulent flow at high Reynolds number around complex shapes undergoing maneuvers and having components in relative motion. The ultimate objective is the prediction of full six-degree-of-freedom maneuvers and the time history of forces on various components, incorporating operation of internal systems, such as ballasting, and control sequences for the propulsor and control surfaces. The present approach obviates the previous extensive simplifications and approximations to the flow physics and can in principle address high Reynolds number flows directly. The flow solver uses an artificial compressibility formulation to solve the three-dimensional time-dependent equations in multi-block transformed coordinates. The overall code is being developed in two parts, a propulsor code and a hull/appendage code, which are being integrated. Both the propulsor and hull/appendage versions of the parallel code are being validated against experimental data and against previous serial code results. The first ever unsteady RANS computation of a submarine undergoing a maneuver under power and in response to a moving control surface is presented. Computations on classified configurations have also been run but not reported here.

Introduction: The Computational Problem

The development of high-speed parallel computers with large memory capacity per node now permits addressing a variety of computational problems previously inaccessible. Unsteady, turbulent, viscous flow at high Reynolds numbers around moving bodies with parts in relative motion could not have been attempted earlier but is now within reach of practical prediction. Such high Reynolds number flow around complex shapes contains an enormous range of length scales and requires high-resolution grids, accurate and stable numerics, turbulence models, and efficient solution per time step. Over the past several years a code has been under development to meet these demands for the important case of the unsteady hydrodynamics of the maneuvering submarine (Davoudzadeh et al., 1997; McDonald and Whitfield, 1996). The prediction of the maneuvering of vehicles and weapons in general must address the flow around components in relative motion, such as control surfaces, as well as the unsteady nature of the flow around the overall body. Forces on the hull, as opposed to lifting surfaces, dominate submarine dynamics, which accentuates the requirement for accuracy in the prediction of three-dimensional separation regions. Also, a large rotating propulsor is an essential component of submarines whose performance must be captured accurately. The complex geometry of the propulsor and its performance in unsteady, nonuniform inflow conditions is a

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challenging problem in its own right, and the unsteady nature of the flow through it in a body-fixed coordinate system is extremely demanding.

This computational project attempts to overcome the limitations of present maneuvering prediction methods which depend on highly empirical approaches, extensive approximations, and model-scale testing which must be scaled in a somewhat ad hoc fashion to the extremely high Reynolds numbers of applications. Of particular interest are severe maneuvers, which are the most challenging to the present methods. The computational solution of the Reynolds-averaged Navier-Stokes equations (RANS) in a fully unsteady (UnRANS) setting can in principle address Reynolds numbers from model scale to full scale. However, to achieve this objective requires efficient and accurate numerics, both in time and space, spatial grids which resolve the important flow features and which accommodate relative motion of components, and turbulence models compatible with the overall solution approach.

Approach

The flow around a powered, maneuvering submarine is highly complex due to the interactions among hull boundary layers, appendage boundary layers and wakes, and the propulsor. Time-dependent trajectories, large angles of attack, and relative motion of components result in a highly unsteady flow. Consequently, the flow fields are represented by the UnRANS equations and solved numerically using the code UNCLE as the primary flow solver both for the overall flow and for the propulsor. This flow solver uses an artificial compressibility formulation to solve the three-dimensional unsteady incompressible equations in multi-block transformed coordinates (Sheng et al., 1997). The parallel implementation uses domain decomposition to partition and map the data space onto a set of processors. Static load balancing is done at the grid generation stage based on a heuristic performance estimator that takes into account the characteristics of the algorithm and the available system resources. The unsteady finite-volume approximation of the governing equations is solved iteratively at each time step using a parallel multigrid/relaxation iteration scheme (Pankajakshan and Briley, 1995). This involves a point-to-point message exchange at each subiteration level. The code uses MPI because of its extensive portability and functionality. The combined propulsor and hull/appendage flow computational routines are embedded in a six-degree-of-freedom (6DOF) dynamic shell to determine at each time step the integrated forces and moments and the resulting change in orientation and trajectory of the vehicle. Future capabilities will include ballast effects, body-force propulsor models, and other features such as flapped control surfaces and near-surface wave forces. Complications in the flowfield include: advanced propulsors such as the turbomachine-like Syrenian concept from MIT (Kirwin et al., 1994); high Reynolds numbers; flow separation at large angles of incidence; and moving control surfaces.

Progress

Progress toward a fully capable code has been achieved in six areas: a re-write of the code in FORTRAN 90 to improve portability and efficiency; incorporation and testing of two-equation turbulence models for more generality and simplicity in setup; flow computation at high angles of drift but steady motion; improvements in complex propulsor computations; development of a body-force propulsor model; and development of a module for moving appendages and the subsequent computation of a rudder-controlled trajectory of a complete propelled submarine. Each of these, detailed below, is an important task leading toward a comprehensive code for maneuvering predictions.

The rewriting of the code in FORTRAN 90 (and MPI) was undertaken to provide features that improve code performance and usability. Dynamic memory reallocation is used to reduce memory requirements and free memory associated with preprocessing tasks. In addition, the number of significant figures is specified, and the namelist capability provides more flexible I/O management. In order for the code to become useable for applications, every effort must be made to improve efficiency and adaptability.

The k-epsilon and q-omega two-equation turbulence models have been incorporated into the parallel code for unsteady flows with turbulence. This is advantageous for potential improvement in predictive accuracy, and these models are less tedious to set up in the parallel code than the algebraic model. The two-equation turbulence models were evaluated by comparison with experimental data for a simple SUBOFF (notional submarine) configuration for incidence angles between -18 and +18 deg. These comparisons are shown in Fig. 1. The q-omega model underpredicts resistance (axial force coefficient) by about 12%, whereas the k-epsilon model is generally within 5%. The lateral force coefficient and the yawing moment coefficient are generally within 5% except at ±18 deg for both models. The source of these errors is under investigation.

A steady (periodic) flow solution is shown in Fig. 2. for a notional (SUBOFF) configuration with rotating propeller and gaps at the control surfaces. The submarine has a fixed orientation to the oncoming flow at 10 deg pitch (down), 10 deg yaw (bow to port) and 5 deg roll (sail to starboard). The Reynolds number is 1.2×10^7. This grid has 4.5 million points, and the solution required 235 time steps per propeller revolution and 4300 time steps per hull length traveled. A steady flow calculation that converges in one hull length of travel (4300 steps) requires 99 hours on 50 T3E/256MB processors (4950 processor hours) at ARSC. The same case run in unsteady maneuvering mode would require 4950 processor hours for each hull length traveled. The code runs at 3.5 GFLOPS on 50 T3E processors with only about 13% communications overhead.

Further simulations have also been performed for the unsteady flow about a notional complex propulsor (the Syrenian geometry, Kerwin et al. 1994). This single-stage propulsor has 11 inlet guide vanes and 6 rotor blades and is being run with a grid of approximately 11 million points using the q-omega turbulence model. This case is being run at AHPCRC because the extra storage required by the q-omega turbulence model is such that 512 Mb processors are required. This solution is shown in Fig. 3. and is the largest T3E case computed to date, requiring 20 hours on 87 processors for 1000 time steps. The current code runs at about 72 MFLOPS per processor, excluding communications overhead. This case requires 22.3 Gb of memory and runs at a net rate of about 4.2 GFLOPS, including the effects of a 20% load imbalance and 15% communications overhead. The parallel solutions typically have communications overhead of only 10-15%. Scalability studies using heuristic performance estimates indicate that on current-generation hardware, parallel efficiencies (percent CPU utilization) of 80 percent and more can be achieved on up to 400 processors and 50 million points, using appropriately-sized grids. A body force propulsor model has also been incorporated into the code and is currently being evaluated. This capability will allow much larger time steps than with a rotating propeller, and this will reduce the run time by more than an order of magnitude.

Solutions for maneuvers induced by control surface movement generally have increased grid size and complexity, due to the control surface gaps and movement. For maneuvering simulations, grids have been generated for a full-configuration SUBOFF geometry with control-surface gaps on the stern appendages and sailplanes, with or without a propulsor. A 4.5 million point grid for a full-configuration SUBOFF geometry with control-surface gaps on the stern appendages and sail planes has been generated for use in a control-surface induced maneuver. Startup solutions have been computed using both k-epsilon and q-omega turbulence models. These solutions represent a straight-line motion at constant velocity that is steady except for the periodic flow unsteadiness induced by the rotating propulsor. This solution is then used as an initial condition for maneuvers induced by a deflection of the control surfaces. The fully-appended SUBOFF/propulsor configuration has realistic control-surface gaps on two sail-planes and four stern-plane surfaces. A startup solution has been run with imposed straight-line trajectory using a k-epsilon turbulence model and with a Reynolds number of 1.2×10^7. This solution for a full-configuration

SUBOFF geometry with realistic control-surface gaps and with k-epsilon turbulence model requires 235 time steps per propeller revolution and 4300 time steps per hull length traveled. This solution requires 99 hours on 50 T3E/256Mb processors (4950 processor hours) for each hull length traveled (4300 steps).

Maneuvering predictions have been obtained for this configuration by coupling the Navier-Stokes flow solver with a 6-DOF solver for the vehicle motion. Integration of the computed viscous stresses and pressure distribution on the body provides the hydrodynamic forces and moments acting on the vehicle. Integration of the 6-DOF equations using these forces and moments yields the time history of the vehicle's velocity and rotation rate. The vehicle's trajectory can then be deduced by integration of purely kinematic relations. Two maneuvering simulations are summarized here for this configuration and grid. The Reynolds number for these solutions is 1.2×10^7. The solution for a maneuver induced by a ten-degree deflection of the rudder is shown in Fig. 4. for four different points in time. These results correspond to a lateral (horizontal) hull deflection of 3, 9, 20 and 30 degrees, respectively.

Summary

Significant advances have been achieved toward computation of the trajectory of a propelled, controlled, maneuvering submarine. The previous success in computations for both the propulsor and the hull/appendage parts of the overall computational problem have been extended in several ways including the first ever computation of the trajectory of a controlled notional submarine. The code has been applied to a more complex propulsor in an unusually large computation of 11 million grid points including incorporation of advanced turbulence models. Presently the full code is being tested for mild maneuvers to develop any required improvements or corrections; it will then be run against model-scale experimental data. The final phase will address emergency recoveries and other extreme maneuvers.

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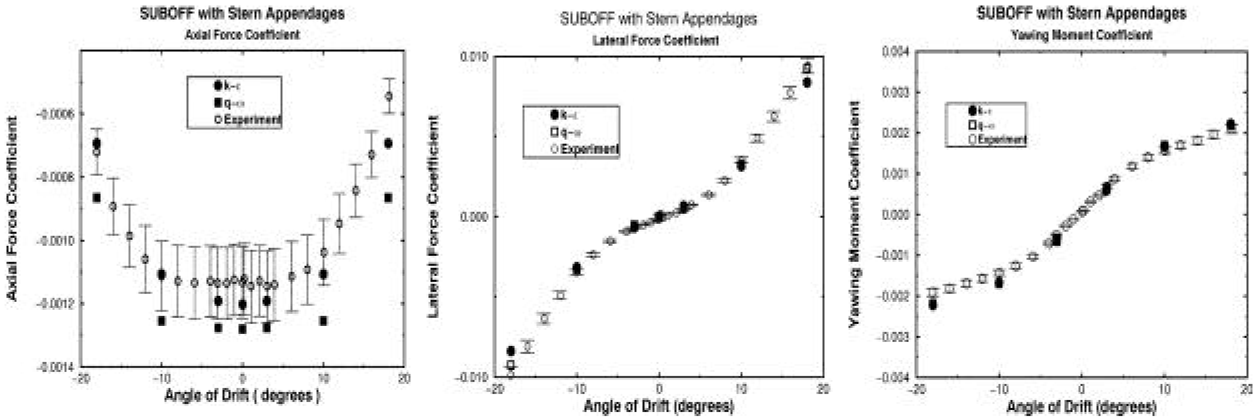


Fig. 1. Comparison with experiment; k-epsilon and k-omega turbulence models.

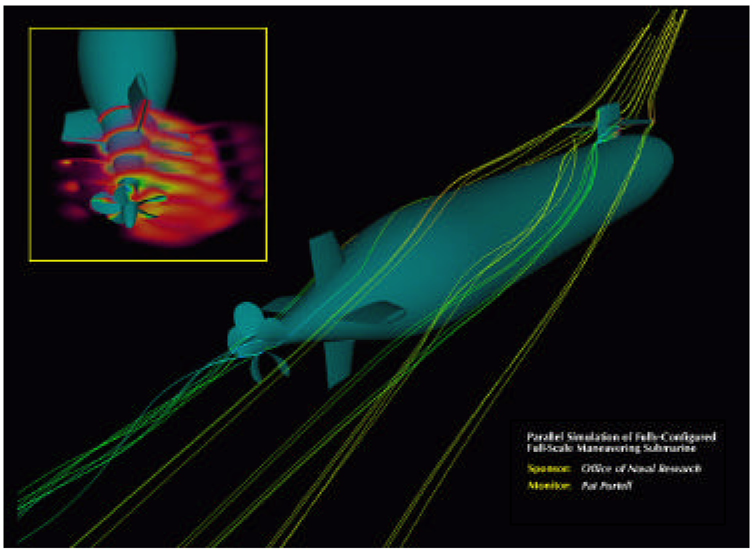


Figure 2. Flow at angle of drift.

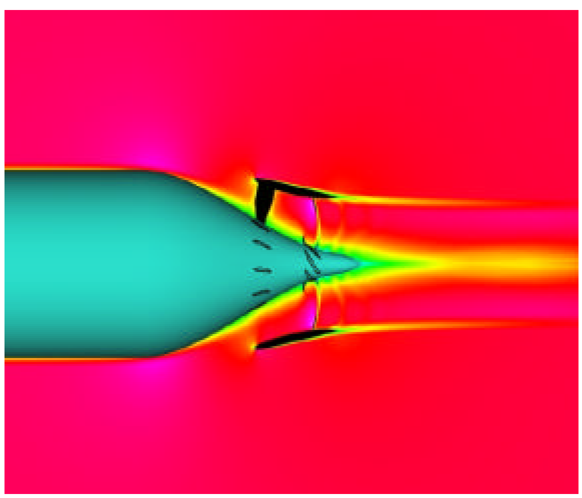
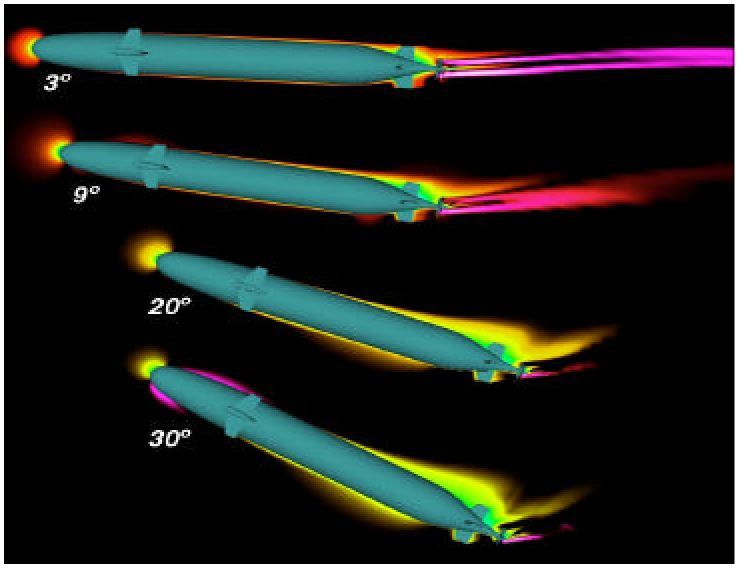


Figure 3. Syrenian propulsor.



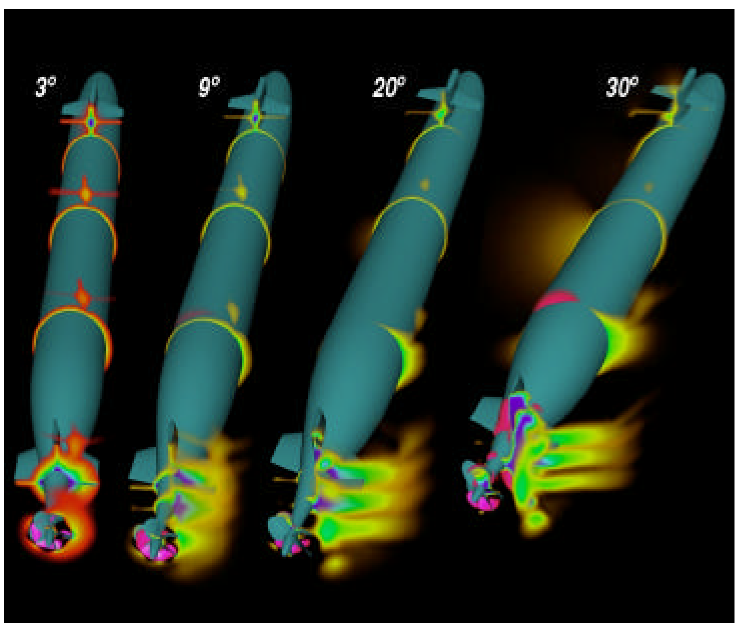


Figure 4. Rudder-induced maneuver at four times and four corresponding angles.